Power-to-Hydrogen and Hydrogen-to-X pathways: opportunities for next generation energy systems

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***Abstract*— Energy systems are evolving rapidly around the world, driven mainly by CO2-e reduction targets. This has led to opportunities for integrated low carbon electricity-and-fuel systems founded on large scale "Power-to-Hydrogen, Hydrogen-to-X" (PtH-HtX). Power-to-Hydrogen (PtH) refers to large scale electrolysis. Hydrogen-to-X (HtX) refers to a range of high value products and services. If these pathways start with low-carbon electricity, then the fuel consumed at the downstream end also low-carbon. Use of intermittently low valued power lowers all production costs. This paper specifically identifies the main pathways and interconnections in a way that overcomes the ambiguities inherent in the term "Power-to-Gas". In turn, this provides solid and easier to understand foundations for building legal and regulatory frameworks for new business opportunities along the lengths of the numerous pathways from supply to consumption.**

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***Index Terms*— energy markets, low carbon fuels, fuel cells, hydrogen storage, load management, power-to-gas**

I. INTRODUCTION

Energy systems are rapidly and substantially changing around the world due to a variety of factors [1-8]:

- Increasing demand for energy worldwide due to globalization and emerging and developing countries;
- Increasing share of renewable electricity production;
- GHG / Carbon dioxide equivalent (CO_2-e) emissions reduction targets;
- Local pollution constraints;
- Deregulation in the energy system, allowing new industries and technologies to enter the market;
- Energy security constraints and system reliability requirements;

- Decentralisation of energy production system (both fuel and electricity).

The balancing of the electricity grid is becoming increasingly challenging with increasing proportions of renewable energy production. Solutions such as transmission super-grids and interconnectors, energy storage ('electrical power to storage to electrical power', (PtStP)), smart grids and demand management, and back-up capacity implementation can certainly support the above transition. However, fundamentally new measures are expected to be needed to manage the grid as proportions of renewable energy sources continue to increase monotonically. Further, the need for decarbonizing the whole energy system, including transport, needs to be considered, as does the difficulties and opportunities from dealing with the requirements in heavy industries. Power-to-hydrogen (PtH) system components thus clearly become part of the broader picture.

Hydrogen production via electrolysis makes it possible to quickly adjust the power consumption: electrolysers can indeed reach full load operation within a few minutes, even a few seconds [9]. They can also decrease power consumption in the sub-second time-frame and thus provide frequency control ancillary services. Another key advantage relative to PtStP technologies is that whereas PtStP just time-shifts the electricity grid balancing challenge, PtH takes the excess renewable power out of the electricity grid once and for all is expected to have benefits under many conditions. Accordingly, hydrogen production is expected to be economically and technically attractive way to contribute to power systems management.

With these anticipated benefits in mind, the Hydrogen Implementing Agreement (HIA) of the International Energy Agency (IEA) approved the creation of "Task 38" at a meeting the 72nd HIA Executive Committee, in October 2015. Task 38 is examining the role of hydrogen as a key energy carrier for sustainable integrated energy systems. The Task is entitled: "*Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the techno-economic, legal and regulatory conditions*". The Task includes contributions from over 50 experts from 34 organizations across 15 countries [10].

The primary objective of the Task is to provide a comprehensive understanding of the numerous economic pathways from intermittently low cost clean power to high value products and services using electrolysis as the first step. Power is becoming increasingly intermittently low in price in regions with high proportions of renewable energy production, due to corresponding periods of excess production relative to demand. The work is accounting for the specifics of geographically different local situations in addition to generic systems analysis. It will also undertake a comprehensive review and assessment of existing legal frameworks. Identifying the local key parameters combined with a various portfolio of different business development opportunities will be a key aspect in the Task. Work will include both the business model evaluation and analysis of the benefits in terms of macro-economic impacts through a systemic approach. A specific objective will be to deliver some general guidelines and recommendations to both business developers and policy makers to enhance hydrogen system deployment in energy markets.

In this paper we use "**low carbon**" as follows: Electrolysis is operationally low CO2-e only if the inherited CO2-e from power used as input to the electrolysis plant is less than the CertifHy benchmark of 36.4 gCO2-e / MJ of hydrogen produced [11]. Similarly, while "**renewable electricity"** can in general refer to a broad collection of energy harvesting technologies, for Task 38 purposes it refers to the two dominant (for economics analysis purposes) technologies of wind and solar power.

The "Power-to-hydrogen" (PtH) concept means that once hydrogen is produced from low carbon electricity, a potentially large portfolio of uses is possible. Applications across diverse sectors include transport, blending with natural gas, and PtStP. Additional products and services include the general business of merchant hydrogen for energy or industry, and provision of ancillary services to power networks. At large scales, PtH can also facilitate deferral of upgrades to distribution and transmission network components.

Accordingly, the primary objective of this paper is to present the "Power to Hydrogen - Hydrogen to X" as broadly as space permits in this context. Our broad approach results in a more rigorous analysis foundation than the "Power-to-Gas" concept which is specific when taken literally, as well as completely general if interpreted to mean "anything". Each pathway is defined and presented in sufficient detail to understand how each opportunity fits into the overall integrated system.

II. THE LIMITS OF THE POWER-TO-GAS CONCEPT

Producing hydrogen from electricity and then mixing hydrogen directly with natural gas, or synthetizing methane by reacting hydrogen with carbon dioxide and then injecting the methane into the natural gas grid, are two key options that are sometimes termed as "Power-to-Gas" [12,13]. However, the "Power-to-Gas" concept is rarely properly and precisely defined. In fact, in the literature Power-to-Gas can refer to power to hydrogen for injection in the natural gas network, or for a range of different applications, sometimes even including fuel for mobility.

Further, Power-to-Gas sometimes exclusively refers to renewable power to hydrogen to gas. At other times this term is used to refer more generally to "excess" or "surplus" power. In yet other instances the term refers to producing hydrogen from power without any quantitative specificity of the CO2-e inherited from the electricity.

To overcome these ambiguities and lack of semantic precision, Task 38 is instead promoting the phrase "Power-to-Hydrogen and Hydrogen-to-X (PtH-HtX)". This keeps "hydrogen" at the center and thus emphasizes its flexibility as an energy carrier and an input industrial chemical production. It also ensures that the monetary value of "gas" does not dominate the perceived value of the processes being investigated. The next section presents an enumeration of pathways from intermittently low value power to high value products and services.

III. Screening the "Power-to-Hydrogen and Hydrogen-to-X" Pathways

A. *The common step: Power-to-Hydrogen*

The common component of all "PtH-HtX" pathways is the Power-to-Hydrogen step.

Hydrogen from electrical power uses electrolysis: a process that until recently has been only deployed at small scales, but 100+ MW systems are now realistic and can be expected to be deployed within a few years. Electrical energy is used to split water into hydrogen and oxygen. Task 38 will review the roles of all electrolysis technologies, primarily: 1) alkaline and 2) proton exchange membrane (PEM), each of which are allocated a full chapter each in [8].

Co-electrolysis [14] refers to the co-production of both hydrogen and carbon monoxide from water and carbon dioxide, from which hydrocarbon fuels can be synthesized. High temperature electrolysis uses cogenerated heat from power production to increase the efficiency of the electrochemical reaction.

The key motivation for developing PtH-HtX pathways is to in turn develop cost effective decarbonization of both the power and fuel sectors of the energy system. Accordingly, PtH needs to be economically and environmentally competitive with other low-carbon production processes, such as emerging solar hydrogen [15] and thermo-catalytic methane decomposition [16], also known as methane cracking, potentially co-producing high purity graphite [17]. In turn, a key to the economic competitiveness of PtH is the intermittent availability of low, zero, or negatively priced electricity. Diverse types of PtH systems can be considered, namely, off-grid, on-grid, and directly connected with a renewable power source with back-up connection to the grid.

B. *Screening the Hydrogen-to-X pathways*

With the aim of decarbonization of a complete integrated energy system covering both power and fuel, all the sectors can be targeted. The three main pathways are the transport sector, the industry sector, and the energy sector (power, gas and heating/cooling).

For the *transport sector*, hydrogen offers diverse pathways for decarbonization. Hydrogen can be used in fuelcells in vehicles, as either the only source of electricity to the electric drive train and any onboard batteries for regenerative braking, or as range extension to plugin battery electric vehicles [18]. Low-carbon hydrogen can also be an input to synthetic liquid fuel production. Similarly, synthetic and biomass sourced hydrocarbon fuel production can be enhanced by using low carbon hydrogen [19,20,21]. Low carbon synthetic fuels are particularly attractive for aviation. Another pathway for the transport sector is the production of synthetic gas fuels, where hydrogen is reacted with carbon dioxide to generate synthetic methane. Again, given that decarbonisation is the key motivation, the life-cycle balance of these systems needs to reviewed with due diligence.

Industrial chemical technologies use hydrogen across many segments. The two major examples are hydrocarbon refineries, and ammonia for fertilizers. Together they represent over three quarters of global hydrogen demand [22]. Most hydrogen consumed to date by these industries has been produced using emissions-intensive steam methane reformation. Other carbon intensive production methods include coal gasification and oil cracking. Clearly, providing low carbon hydrogen with PtH would decrease the carbon footprint of these industries.

Finally, the versatility of low carbon hydrogen can make it a unique energy carrier for contributing to the decarbonisation of the entire energy sector in the broadest sense: power, fuel, and heating/cooling.

After having been generated from low carbon power, hydrogen can be used to regenerate clean electricity through fuel cells or gas turbines. Power production from hydrogen is particularly promising for off-grid applications (e.g. supply of remote communities and back-up power). But for grid-connected applications, a very large difference in power buy/sell price is required for PtHtP to be competitive.

Low carbon hydrogen can contribute to decarbonizing gas supply through blending. Two options are open. The first option is to directly blend hydrogen with natural gas in the natural gas grid. The amount of hydrogen that can be directly injected is limited. The second option is to inject synthetic methane produced from methanation, in which low carbon hydrogen is reacted with carbon dioxide (or also in principle, carbon monoxide). The scale of this second option is unbounded with respect to proportions injected.

Finally, hydrogen can also be used to for heating and cooling, and for combined heat and power (CHP) applications.

A visualization of the main PtH-HtX pathways with interconnections from low carbon intermittently low valued electricity to (potentially) high valued products and services, is presented in Figs.1 and 2.

C. *Expanding the value chain via the provision of ancillary services*

As also presented in Figs. 1 and 2, extra revenues from PtH could potentially be obtained by providing system support services to the grid, in particular "Frequency Control Ancillary Services" (FCAS) (see for instance [23]) concurrently with hydrogen production. Depending on the specific power system and market, different types of ancillary services may be required which can potentially be provided by PtH. These include primary and secondary frequency response (usually with a collection of event-response times in the order of seconds, tens of seconds, and minutes), as well as different types of reserves with event-response times in the order of minutes, and tens of minutes. Recently, new fast frequency response services are also emerging (see for example [24,25]). The event-response times for these are in the sub-second time scale, particularly to address a loss of system inertia in the presence of high instantaneous penetration of renewable electricity output, which exacerbates the frequency balance challenge. These services could be provided by electrolyzers that represent the initial step in all PtH pathways.

By providing FCAS, PtH could thus enable both the productive consumption of excess renewable power when demand is low, and grid security and reliability services that overcome the resistance by some to the ongoing deployment of increasingly high proportions of renewable power capacity.

IV. Conclusions: PtH-HtX opportunities for the energy system and beyond

The main drivers for Power-to-Hydrogen and Hydrogen-to-X is decarbonizing the energy system and productively enabling ongoing increases proportions of renewable power capacity. This paper discussed the potential role of hydrogen systems to decarbonize the transport, industry and energy sectors (power, gas, and heating/cooling). Assessing the hydrogen potential on each of the identified sector, as well as the feasibility for hydrogen to enter the identified markets was beyond the scope of this paper. The aim was rather to highlight the potential of hydrogen of being a key enabler towards a low-carbon economy.

In this context, this paper has begun to precisely identify the main PtH-HtX pathways that can be considered, in order to overcome the ambiguities related to the phrase “Power-to-Gas”. Each pathway has been defined in order to examine the associated opportunity for the energy system. Specific attention is given to the definitions of the words and the interconnections along the main pathways, to prepare for providing inputs to future Codes and Standards committees, and to provide solid foundations for building legal and regulatory frameworks for new business opportunities. This is an ongoing work of Task 38, through the collaboration with the standardization organizations CEN (the European Committee for Standardization) and CENELEC (the European Committee for Electrotechnical Standardization).

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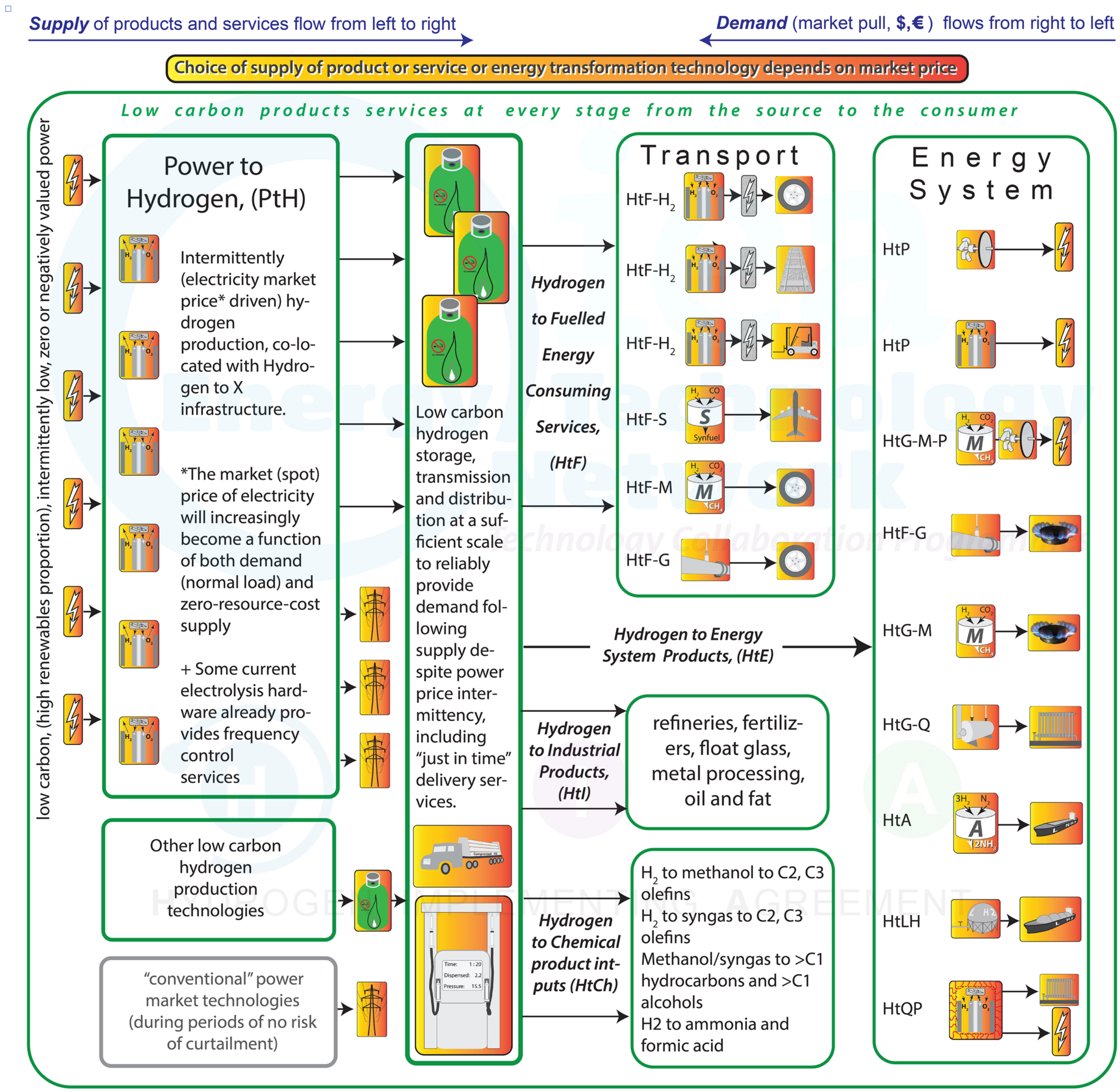

Figure **1**: PtH-HtX: Enumeration of the main pathways from low carbon, intermittently low valued power to high value products and services

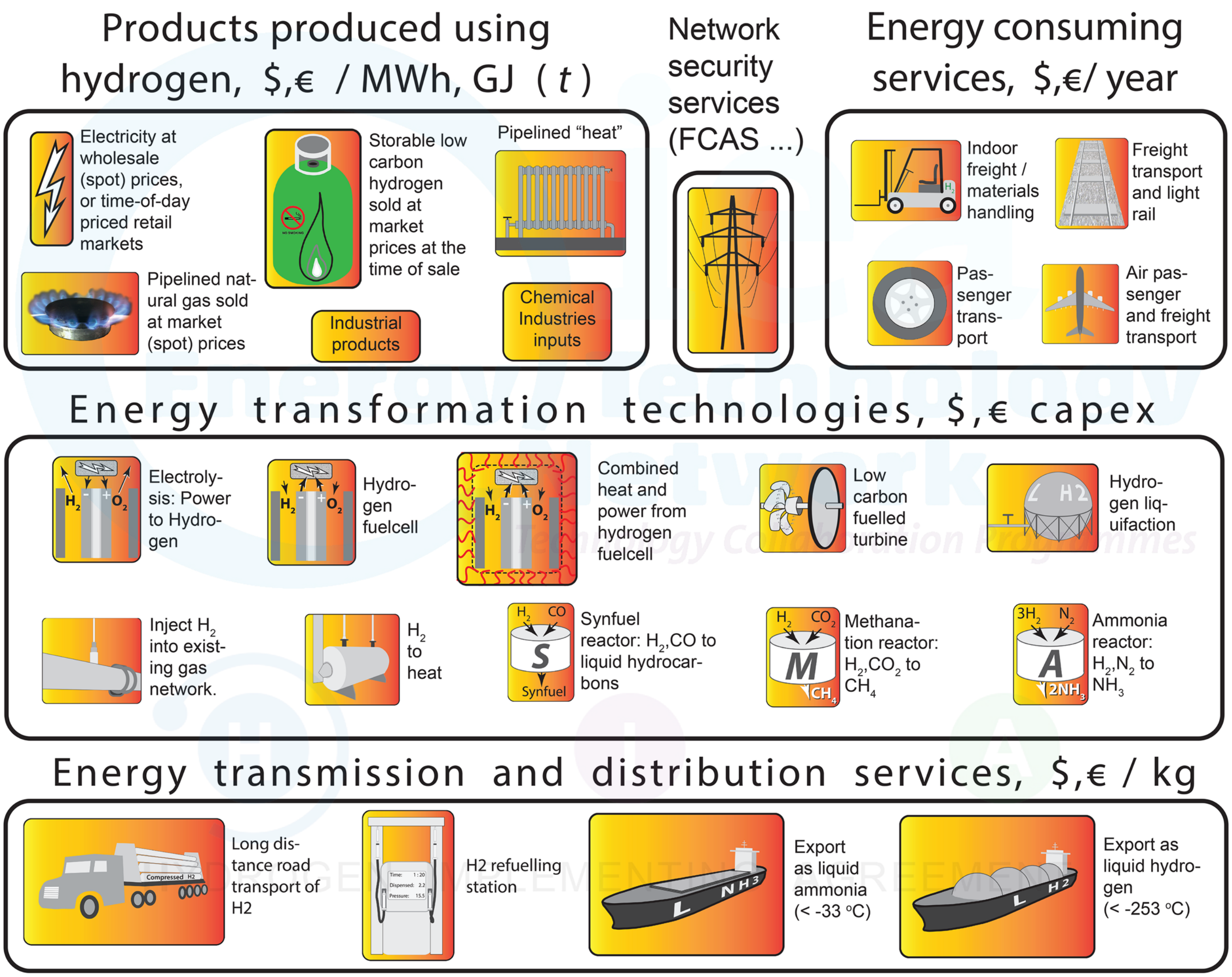

Figure **2**: PtH-HtX: Icons legend of products, services, and energy transformation technologies